Int J Life Cycle Assess (2011) 16:569–579
DOI 10.1007/s11367-011-0289-3

CARBON FOOTPRINTING

Case study on the carbon consumption of two metropolitan cities

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Received: 9 June 2010 / Accepted: 13 April 2011 / Published online: 3 May 2011

Abstract

Purpose The cities merit special attention in global warming since they produce up to 80% of the global greenhouse gas emissions. Even though this has been widely acknowledged, only few papers exist that have studied cities holistically from a demand, i.e., consumption, perspective. The study presents a detailed analysis of the carbon footprint of two metropolitan cities from a consumption perspective. With the analysis of consumer carbon footprints (carbon consumption), the distribution of emissions in the key source categories is presented and compared.

Materials and methods The study utilizes Finnish consumer survey data by cities, regional emission data for key processes, and general emission data to produce a hybrid LCA model for a holistic assessment of city-level greenhouse gas emissions from the consumption perspective.

Results and discussion The study results showed the carbon consumption to be 13.2 t CO2e per person in Helsinki with a 17,400 € annual consumption expenditure and 10.3 t CO2e per person in Porvoo with a 15,900 € annual consumption expenditure, respectively. The dominant carbon sources for metropolitan living are heat and electricity, building and property, private driving, and services. Within the cities, some significant differences were found. The carbon emissions from energy consumption are 4.5 t CO2e for an average consumer in Helsinki, whereas an average consumer in Porvoo only causes 2.0 t CO2e due to the cleaner energy production in Porvoo. On the other hand, private driving causes 2.0 t CO2e in Porvoo, but only 1.3 t in Helsinki. The overall trip generation in Helsinki is only half of that in Porvoo, and also, the usage of public transport is at a substantially higher level in Helsinki. The current results contradict interestingly some earlier studies in finding that the theoretical carbon-reducing influence of city density is overridden with other factors, such as the type of energy production, energy efficiency of the housing stock, and increased use of services. In our study, Helsinki represents a metropolitan area with a denser structure and a more efficient public transport system, but still consuming around 25% more carbon emissions than the other city in the metropolitan area, Porvoo. The sensitivity analysis showed that even with the normalization of the key parameters between the two cities, the main finding still holds.

Conclusions The evaluation of the carbon footprint of cities from the consumption perspective, instead of a more traditional production perspective, seems to offer an interesting new insight into the carbon footprints of the cities. It identifies similar key sources of carbon as production-oriented studies but further emphasizes the significance of the utilized services in the carbon footprint evaluations. In the future, the carbon footprint of services, especially in the service-intensive economies and cities that tend to outsource their manufacturing and carbon emissions, should be further examined since they cause an ever increasing proportion of the carbon consumption of consumers.

Keywords Climate change mitigation · Carbon footprint · Consumption · Green cities · Hybrid LCA · Urban structures

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1 Introduction

Global warming may be the most severe environmental problem on a global scale. Already in 2007, The Intergov-

ernmental Panel on Climate Change concluded with over 90% certainty that climate change is driven by greenhouse gasses (GHGs) from human activities (IPCC 2007). Thus, the recognition, prevention, and mitigation of GHGs form one of the greatest challenges of the near future (European Commission 2009; UN 2009).

Cities produce a major share of the greenhouse gasses at a global level (Kennedy et al. 2009; Dodman 2009) as cities have been estimated to produce up to 80% of the total emissions (UN 2007). They also seem to offer the greatest mitigation possibilities (UN 2007; Kennedy et al. 2009). While many cities have recognized their important position (Mayor of London 2010; Pajunen 2008; European 2009; Kerkkänen 2009), few studies exist that show how the potential could be capitalized in a globally sustainable manner.

A number of environmentally oriented studies have addressed the fields of industrial ecology, with an emphasis on urban metabolism (Kennedy et al. 2007), urban planning (Rijsberman et al. 2006), green construction (Kay 2002), and transportation (VTT Technical Research Centre of Finland 2010; Lave et al. 2008) examining climate change prevention possibilities. While they have brought up prominent information, they rarely offer a holistic systems approach that would enable effective carbon management at city level. For example, production-focused studies easily lead to biased conclusions, suggesting that the outsourcing of carbon-intensive industries would be a good climate mitigation strategy for metropolitan areas (Kennedy et al. 2009; Dodman 2009).

Whereas some studies exist where a holistic approach has been taken to assess the consumer carbon footprint, i.e., carbon consumption (we introduce the term carbon consumption to differentiate our results from the production-oriented carbon calculations) with the emphasis on regional carbon emissions (Cicas et al. 2007; Weber and Matthews 2008), the utilized input–output-based life cycle assessment (IO-LCA) methods cannot easily be exploited on city scale. On the other hand, the results process-based life cycle assessments (LCAs) suffer from biases due to a truncation problem, in addition to being very laborious to conduct in a complex system context (Suh et al. 2004; Junnila 2006a, b).

With this study, we fill a gap in existing research. First, we advance the research in city-level LCA studies by proposing a new enhanced input–output hybrid LCA model for assessing city-level carbon footprints from the consumption perspective. Consumption-oriented LCA enables a systems approach that allows the testing of climate change mitigation strategies that lead to sustainable solutions from a global perspective. Second, we open a discussion on the results of earlier city-level studies that have found urban density as the key element for lower carbon emissions (Dodman 2009; Norman et al. 2006). We demonstrate here with two case studies how sensitive these results are to other factors, such as emissions from regional and household energy production and the amount of services consumed to replace traditional household-related activities. In addition to these, our study sheds light on the division of the consumer carbon footprint into emissions related to both lifestyle and urban structures.

We consider the present approach relevant for various levels in the society. First, our proposed hybrid LCA model advances knowledge on city- and regional-level emission assessment. Second, the study delivers new information on the sources of carbon emissions and their allocation to consumption. Finally, the consumption-oriented approach allows us to reduce significantly both the truncation problem of process-based LCAs as well as to avoid the influence of outsourced emissions at city level.

Our study advances in three phases. First, we create the proposed hybrid LCA model to assess city-level carbon consumption. After this we construct the carbon footprint of an average consumer for the two case cities: Helsinki, the capital and the largest city in Finland, and Porvoo, a smaller city closely connected to the Helsinki economic region. In the third phase, we run a sensitivity analysis both to check the robustness of the results and to demonstrate some climate change mitigation potentials related to urban living.

2 Design and methodology of the study

This study was conducted utilizing a life cycle assessment method. More specifically, we created a new hybrid LCA model for the assessment of carbon emissions at city level, starting from the Carnegie Mellon University's economic input–output LCA model (EIO-LCA) (Carnegie Mellon University Green Design Institute 2008). While LCA has become a widely accepted method for assessing the environmental aspects of goods or services (Cicas et al. 2007; Suh et al. 2004; Junnila 2006a, b) by taking into account the entire life cycle effects of the studied system, different approaches exist within LCAs.

The conventional way of conducting an LCA is process LCA (Suh et al. 2004; Junnila 2006a, b; Joshi 1999). In process LCA, the emissions of a certain action or good are assessed process by process based on energy and mass flows. The method is accurate if conducted properly, but the results may also be biased due to the truncation problem, as the system boundary always needs to be set. The cutoffs may potentially have a significant impact on the results of the assessment (Suh et al. 2004).

The truncation problem can be avoided by using an input–output LCA method (Joshi 1999). The method takes into account the whole economy, using sectorial monetary transaction matrices that describe industry interdependen-

cies within an economy (Joshi 1999). Compared to process LCA, the method is quick and rather easy to use (Junnila 2006a, b). While this approach is appropriate for conducting an LCA following the ISO guidelines (Suh et al. 2004), some problems exist. A high input data aggregation level together with possible temporal (inflation and currency rate differences) and regional (industry structure differences) asymmetries in the data and the model are the primary sources of uncertainty.

Hybrid LCA models have emerged to combine the strengths of the latter two approaches and to reduce the weaknesses related to them (Suh et al. 2004; Sharrard et al. 2008). There are several ways to conduct hybrid LCAs. In a tiered hybrid analysis, “the direct and downstream main requirements and some important lower order upstream requirements are examined in a detailed process analysis while remaining higher order requirements are covered by input–output analysis” (Suh et al. 2004). In an input–output-based hybrid analysis, the output sectors are disaggregated to include process data and to avoid the aggregation and truncation problems. Joshi (1999) describes the method in detail and demonstrates its use (Joshi 1999). Finally, an integrated hybrid analysis model incorporates process-level information into the input–output model (Suh et al. 2004).

The hybrid LCA model we propose in this study is an application of the tiered hybrid analysis. The Economic Input–output Life Cycle Assessment US 2002 Industry Benchmark model of Carnegie Mellon University’s Green Design Institute (2008) forms the basis of our hybrid model. This model was selected as the basis since it provides the most disaggregated sector selection with 428 industry sectors. It also seems to be a suitable approach to start analyzing cities in small foreign trade-based economies, such as Finland, where more than 50% of the value of the total consumption is oriented to import goods (Statistics Finland 2009a, b).

In our proposed hybrid model, the input–output sectors with a significant impact are enhanced with process data. To fully capitalize the benefits of IO-LCA, our hybrid model is input–output-based, but we have substituted key subsector data with specific process data. The rest of each output matrix is left untouched. This way, we have managed to significantly reduce the truncation and aggregation problems at the same time. The construction of the hybrid model is further described in the next section.

The study consists of three phases. First, the hybrid LCA model was created. Then, the carbon consumption (carbon footprint) of an average consumer of the two case cities, Helsinki and Porvoo, was assessed. In the last phase, we demonstrated how our model indicates that some earlier studies remain incomplete to some extent concerning city-level climate change mitigation possibilities.

Two Finnish cities, Helsinki and Porvoo, were chosen as the case study cities since they provide an excellent basis for the purpose of this study due to both regional factors and data availability. The first of the cities, the Finnish capital Helsinki, represents the core of the metropolitan area with efficient and diverse public transportation including metro, commuter train, tram, and bus connections. Helsinki is the center of the Helsinki metropolitan area with over 1,000,000 inhabitants with a rather high standard of living (17,400 € per capita private consumption in 2006 (Statistics Finland 2007)). Porvoo is a small city (50,000 inhabitants) 50 km east from the center of Helsinki with a high dependability on Helsinki, with almost 25% of the workforce commuting to the Helsinki metropolitan area daily (Uusimaa Regional Council 2009). The city’s public transport options are limited only to busses. The standard of living in Porvoo is slightly lower than that in Helsinki (15,900 € per capita private consumption in 2006 (Statistics 2007)). Some key figures of Helsinki and Porvoo are presented in Table 1.

The primary input data used in the model are the Finnish consumer survey 2006 data (Statistics 2007). The data include the annual consumption expenditures of an average consumer divided into approximately 1,000 categories and subcategories. The data are available on a national, regional, and city/municipality level. The city/municipality-level data were used in this study. Process data were collected from a number of sources described further as they appear.

The study started with an aggregation of the input data. The overall consumption was grouped from the original 1,000 categories into 41 initial categories that were matched with the EIO-LCA 2002 industry sectors to create a first direct input–output-based carbon footprint of an average consumer. To avoid biases caused by temporal factors (inflation and currency rate differences) between the Finnish 2006 based input data and the US industry 2002 model, a purchasing power parity (PPP) correction was made based on data provided by The World Bank on year 2006 (International Comparison Program (ICP)). These 41 initial categories were then grouped further into 10 major consumption classes, starting from housing- related lifestyle

Table 1 Key figures of the two case cities

	Helsinki	Porvoo
Inhabitants	550,000	48,000
Inhabitants per square kilometer	3,010	73
Living space/inhabitant (m^2)	34.2	39.1
Private consumption (€)	17,400	15,900

issues (building, purchased energy, etc.) and continuing all the way to more general consumption. The classes are:

1. Heat and electricity
2. Building and property
3. Maintenance and operation
4. Private driving
5. Public transportation
6. Consumer goods
7. Leisure goods
8. Leisure services
9. Traveling abroad
10. Health, nursing, and training services

Of the 10 classes, heat and electricity comprise all housing-related energy use, including privately paid household heat and electricity as well as the relevant proportion of the communal building energy. The building and property class consists of construction and planning, whereas maintenance and operation comprise the expenses of repair works, waste, water, and property management. Private driving includes all expenses related to driving, purchases, and the maintenance of private vehicles. Public transportation contains other domestic traveling, except private driving and traveling abroad. Goods and services classes comprise daily consumption and consumption of durable goods, so that leisure-related expenses are separated for a demonstration of the allocation of emissions and lifestyle differences. Traveling abroad includes flying and accommodation abroad. Finally, health, nursing, and training services form together an expense class where free or heavily subsidized public services dominate consumption, and the monetary expenses consist primarily of private sector charges.

At this point, we conducted a direct EIO-LCA carbon footprint calculation. Based on the results of this preliminary carbon footprint modeling, the direct EIO-LCA model was enhanced to form a hybrid LCA using tiered LCA method (Suh et al. 2004). The categories hybridized were heat and electricity, building and property, maintenance and operation, and private driving and public transportation, which together accounted for roughly 70% of the carbon footprint in the preliminary IO calculation. The enhancement process on each class is described below.

The heat and electricity consumption class comprises all housing-related electricity and heating expenditures. In Finland, a notable share of these is actually embedded in rent and housing management charges. To avoid the bias of omitting these from energy consumption, these expenditures were moved to the energy category according to the comprehensive study by Kiiras et al. (1993) and an updating study conducted by us with the financial statements of 10 housing corporations located in the Helsinki metropolitan area. The average share of the energy costs of the overall maintenance and operation costs was found to be approximately 25% of the annual housing management charges. After this correction, the energy class was divided into the energy production phase and other life cycle phases according to the Finnish Environmental impacts of material flows caused by the Finnish economy (ENVIMAT) study (Seppälä et al. 2009). Of these two, the production phase figures for both electricity and heating were replaced by process emission data announced by the local producer (Statistics 2009a, b; Finnish Energy Industries 2007; The Finnish Ministry of Trade and Industry 2007). For other secondary sectors, the original EIO-LCA power generation and supply matrix was utilized (Carnegie Mellon University Green Design Institute 2008). The division of emissions from combined production from electricity and heat was made according to the energy principle. To avoid any double counting of emissions, an emissions coefficient was calculated using 2006 consumer prices to maintain the monetary basis of the model.

The second consumption class enhanced was building and property. Here, the property costs discounted on an annual level were divided into the value of actual construction (the building) and the site (the value of the land), as the difference in the carbon emissions related to the two is significant. The division was made according to the statistics published by The Housing Finance and Development Centre of Finland (ARA) (2006).

As the third step, the maintenance and operation class costs were extracted from the consumption data and divided into more detailed categories. Technically, lease payment and housing management charges were disaggregated according to Kiiras et al. (1993) and the financial statements study mentioned above. These operation expense data were then matched with the suitable EIO-LCA sectors. Here, as described, the process was based mainly on the disaggregation of the input data rather than tiered hybridization.

The next step in the creation of the hybrid model was the implementation of the process data to the consumption class of private driving. Here, the emissions from fuel combustion and petroleum refining were separated first and then assessed. The combustion emissions were calculated using process data from the Finnish LIPASTO study (VTT Technical Research Centre of Finland 2010). Again, to maintain the monetary basis of the model, an emission coefficient was calculated using 2006 gasoline prices (Statistics 2009a, b; Finnish Financial Advisors 2009). For the refinery process, the EIO-LCA sector Petroleum refineries was used for the producer price share (Wikipedia 2009) of the total expenditure.

The fifth and final consumption class enhanced for the hybrid model was public transportation. There, as the emission profile of Finnish public transport differs signif-

icantly from that of the USA, we replaced the whole EIO-LCA with the ENVIMAT (Seppälä et al. 2009) sectors for coach and taxi trips and railway and metro trips. For the division of the public transport expenditure between these sectors, we used data from The National Travel Survey 2004–2005 (WSP Finland Ltd 2005).

After the hybridization process, we calculated the carbon footprints, or carbon consumption, of living lifestyles in the two cities of Helsinki and Porvoo with the hybrid LCA model. The results were then evaluated with a sensitivity analysis.

3 Results

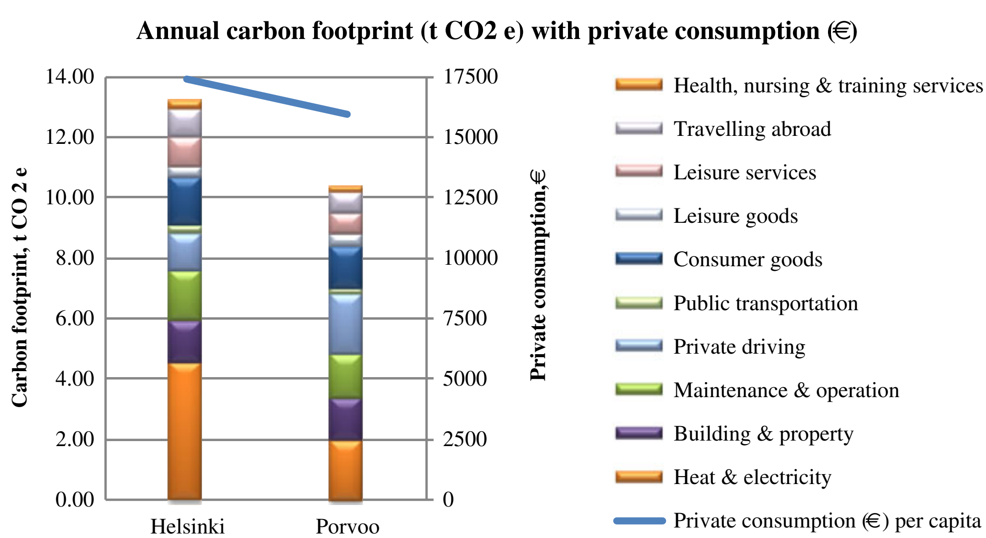
According to the hybrid LCA model, the carbon footprints differ quite heavily between Helsinki and Porvoo on a per capita basis. The carbon consumption of an average consumer living in Helsinki is 13.2 t of carbon dioxide equivalents (tons CO2e), while that of an average consumer in Porvoo is 10.3 t CO2e. The difference in the standard of living (Helsinki, 17,400 €; Porvoo, 15,900 €) explains part of the dissimilarity, but a major share is also due to differences in urban structures and in the lifestyles influenced by these structures. These differences seem to be an interesting question as the overall result connects higher density and higher emissions. Another interesting notation is that the services alone, which are often scoped out from carbon emission studies of cities, produce over 20% of the emissions in the case cities.

Despite the differences related to the level of carbon consumption, Fig. 1 shows that in both cities, two thirds of the carbon footprint is related to the four major consumption categories—heat and electricity, building and property, maintenance and operation, and private driving. Of the four major categories, heat and electricity is the most important emission-producing category for a consumer in Helsinki (4.5 t CO2e), but only 2.0 t in Porvoo. Building and property creates a carbon footprint of 1.4 t in both cities, and the maintenance and operation class creates 1.6 t CO2e emissions in Helsinki and 1.5 t in Porvoo. Private driving accounts for nearly 2 t of the CO2 emissions in Porvoo, while in Helsinki, the figure is only 1.3 t CO2e.

The most notable difference is found from heat and electricity, according to our model. This difference is explained by carbon intensity of energy production. The intensities are 284 g/kW h for electricity and 286 g/kW h for heat in Helsinki, and 65 g/kW h for electricity and 92 g/kW h for heat in Porvoo when calculated with the energy method (Statistics 2009a, b; Finnish Energy Industries 2007; The Finnish Ministry of Trade and Industry 2007). The difference arises from local fuel combustion. More than 70% of the fuels used by Porvoon Energia are renewable, while the dominant fuels for Helsingin Energia are coal and gas. The annual expenditure on energy is roughly the same in both cities, 670 € in Helsinki and 650 € in Porvoo (Statistics Finland 2007).

When energy is separated from the analysis, the carbon emissions from other building-related sources, building and property and maintenance and operation, are very similar between the cities. Together, they account for 20–30% of the total emissions in both cities. The division of the overall emissions of approximately 3.0 t CO2e seems to be roughly 50–50 between the two classes. As the emissions in building and property class are almost entirely emission of construction, the result indicates that the importance of the construction phase is higher than has been reported earlier. Several earlier studies have concluded that the construction

Fig. 1 Annual carbon consumption of Helsinki and Porvoo with private consumption



phase (including materials) accounts for around 10% or less of the overall life cycle GHG emissions of a building (e.g., Junnila et al. 2006; Sharrard et al. 2008). However, in those studies, a long theoretical life span (typically 50 years) is assumed for buildings. Based on our study, it seems that in an urbanizing region, the average life span is significantly shorter. Also, an interesting finding in our study is the minor share of emissions from waste and waste water that together with water account for only 7% of the overall emissions of the maintenance and operation category alone.

A second clear difference in emissions, in addition to heat and electricity, is found from private driving. Trip generation in Porvoo (over 18,000 km/a) is more than double of that of Helsinki (roughly 8,000 km/a) (WSP Finland Ltd 2005). The main explanations for the difference are the location, urban structure and public transportation. Porvoo is located 50 km from Helsinki, but both working in the Helsinki metropolitan area and leisure visits are common. The urban structure of Porvoo is less dense than that of Helsinki (City of Porvoo 2009; Helsinki Region Infoshare 2007; Statistics Finland 2009a, b), which also increases the need for transportation. In Porvoo, private driving dominates all traveling (Statistics 2007), while in Helsinki the availability of diverse and effective options of public transportation diminishes private car usage (Statistics 2007; Helsinki Regional Transport Authority (HSL) 2009).

The importance of emissions from the category of Public transportation seems relatively small, but the category is important especially as an alternative for private driving. The emissions from this category are roughly the same for both cities, 0.2 t CO2 e, but the per capita trip generation in Helsinki is slightly over 3.000 km/a, while in Porvoo the figure is less than 2,000 km/a. In Helsinki, almost 50% of all these kilometers are traveled on the rails, whereas 98% of the use of public transportation in Porvoo happens by coach (Statistics 2007), and, according to our model, traveling on the rails is 25% cleaner in the GHG emissions than traveling by coach (Seppälä et al. 2009).

The rest of the consumption classes, Consumer goods, Leisure goods, Leisure services, Traveling abroad, and Health, nursing and training services account for one fourth of the total GHG emissions. These are the categories that are often left out in production oriented carbon studies. However, some of them are closely related to living lifestyles. Our results indicate that in more urban environment lifestyles consumers tend to “outsource” their direct carbon emissions to services. For example, eating outside instead of at home, going to movies instead of watching DVDs at home and using health and beauty services instead of relaxing at home. These outsourced services produce roughly 1.0 t CO2 emissions in the more urban Helsinki and 0.7 t in Porvoo.

Another interesting notion, although in accordance with some earlier results (Kerkkänen 2009; Carnegie Mellon University Green Design Institute 2008), is that it would seem that the carbon intensity of services is only moderately lower than that of goods, around 15% in our study. This would indicate that a shift in consumption from goods to services would have only moderate effect on the overall carbon consumption.

4 Sensitivity analysis

We pointed in chapter 4 that in the light of our results it seems that the correlation between city density and carbon emissions reported in earlier results might be weak. To validate this observation, and to check the robustness of our results, we conducted a sensitivity analysis.

The analysis was conducted for three dominant factors in the case study results: the transportation choices, the type of household energy used (Heat and electricity class) and the living space density (Building and property, Maintenance and operations). Below is a description of each step of the analysis. The results are also collected in Table 2 at the end of this chapter.

The analysis started from the transportation choices and included a scenario on the effects of better public transportation, especially rail based connections, on private driving and its emissions. Many higher impact changes, such as the total abandonment of private driving and electric cars, were left out of the analysis.

In the base case scenario, the carbon footprints of average consumers are 13.2 t CO2e in Helsinki and 10.3 t in Porvoo according to our model, as was shown earlier. Private driving adds a share of 1.3 t of CO2 e to the carbon footprint in Helsinki, i.e., 10% of the total emissions, and 2.0 t in Porvoo, i.e., almost 20% of the total carbon consumption. In Helsinki, the dense urban structure and the availability of diverse public transport choices are seen in low private driving trip generation (8,000 km/a/consumer, the lowest in the Helsinki economic region (Statistics 2007)). Notable differences exist between the downtown core and the suburbs, however. The annual private driving trip generation in downtown is 40% lower than that in suburbs (Helsinki Regional Transport Authority (HSL) 2009). If this difference is used as a broad estimate, better public transport would lower the average carbon footprint by 0.3 t CO2e.

For Porvoo, the annual private driving trip generation of 18.000 km/consumer is the highest in the Helsinki economic region (Statistics 2007). An estimation of the effect of better public transport connections can be estimated by analyzing the structure of transportation of other cities within the Helsinki economic region. It would

Table 2 The results of the sensitivity study, tons of CO2 equivalent

Factor	Results, t CO2e	
	Helsinki	Porvoo
Average consumer carbon footprint	13.2	10.3
Private driving, downtown core comparison	12.9	–
Private driving, the effect of a train connection	–	9.8
Energy emission profile normalized to the Finnish average	13.0	12.4
Average energy emissions with private consumption normalized to the level of Porvoo	11.9	12.4
More dense living (based on the Tokyo reference)	12.1	9.2

The − indicates that the scenario is not suitable for the corresponding area

seem that the important factor affecting the trip generation is commuter train connection. In two cities, Kerava and Hyvinkää, situated 30–50 km away from Helsinki like Porvoo, the private driving trip generations are 30–40% lower than those of Porvoo and Nurmijärvi (Statistics 2007), cities within the same distance from Helsinki but without a train connection. Even assuming no change in the number of cars/consumer, a commuter connection would seem to decrease the per capita carbon consumption by 0.4–0.5 t CO2e in Porvoo.

Next, we analyzed further the sensitivity of the results related to energy. The sensitivity for the emissions from energy production is high. It alone seems to be enough to reverse the positive influence of higher density. It has been noted in earlier studies that more dense urban structures correlate strongly with lower emissions (Dodman 2009; Norman et al. 2006). For instance, in their study on the effect of density on carbon emissions, Norman et al. (2006) reported that low-density suburban development is as much as 2–2.5 times more GHG intensive than a high-density urban core on a per capita basis. Our case studies show contrary results, demonstrating that this result will not hold, at least under certain conditions.

The energy production in Helsinki relies heavily on coal and gas, whereas over 70% of total production in Porvoo is based on renewable sources, the emissions being 284 g/kW h for electricity and 286 g/kW h for heat in Helsinki, and 65 g/kW h for electricity and 92 g/kW h for heat in Porvoo (Statistics Finland 2009b; Finnish Energy 2007; The Finnish Ministry of Trade and Industry 2007). The average in Finland is 240 g/kW h for electricity and 286 g/kW h for heat (Kurnitski and Keto 2010, submitted). If we now use the average energy emission profile for both cities, the footprints become 13.0 t for Helsinki and 12.4 t for Porvoo. The remaining difference mainly reflects the difference in disposable income, as the carbon footprint of Helsinki drops down to 11.9 t when the level of consumption is normalized to the level of Porvoo. However, as the footprints from energy use alone would be 4.4 t CO2e in Helsinki and 4.0 t in Porvoo with the average profile, the reverse result still holds.

When arguing that living space density will not necessarily lead to lower emissions, it needs to be noted that there exists a connection ceteris paribus. Smaller living space would affect the carbon consumption in three ways. First, emissions from maintenance and operation would be reduced, following linearly the cutoff in the living space. Second, the cutoff in space would affect the energy consumption. Third, more dense living would reduce construction phase emissions. The impact would also be on both electricity and heating as both correlate with space. If we assume a linear connection, the total impact of cutting living space would be approximately 0.2 t CO2e/m^2 in Helsinki and 0.1 t/m^2 in Porvoo. For an impact scenario, we used a living space reference from Tokyo, where high density is strongly an urban structure-related situation instead of arising from poverty. In Tokyo, the average living space is 28.9 m^2 (Japan Statistics Bureau 2010), meaning reductions of 5.3 m^2 in Helsinki and 10.2 m^2 in Porvoo.

5 Discussion

In this study, we presented an application of a tiered hybrid LCA model for assessing carbon consumption in metropolitan areas. The purpose was to advance research on city-level carbon footprint modeling and to test the robustness of earlier results on the connection between living density and carbon emissions. With the hybrid model, we were able to create a detailed consumer carbon footprint and demonstrate the division of the emissions into urban structure and living lifestyle-related emissions. In addition, we demonstrated with two case studies that the common result of a correlation between density and emissions

reported earlier in several studies is highly sensitive to structural factors, such as the type of energy used.

We approached the assessment of carbon consumption from an end-user viewpoint with an urban development perspective, as cities produce a majority of the global GHG emissions (UN 2007; Mayor of London 2010) and seem to offer the greatest mitigation potential (Kennedy et al. 2009; UN 2007). Production-based assessments on city and other regional levels (Dodman 2009; Kates et al. 1998) easily lead to quite problematic conclusions, such as the suggestion that the outsourcing of carbon-intensive industries would be a good climate mitigation strategy for metropolitan areas. Our stance is that as climate change is a global problem, the location of the emission source is irrelevant, and thus, only demand-based assessments lead to sustainable policy solutions globally.

The carbon emission assessment was conducted for two average consumers in the selected case cities of Helsinki and Porvoo, representing two competing types of metropolitan areas in Finland. The study resulted in a carbon footprint of 13.2 t CO2e per person in Helsinki with a 17.400 € annual consumption expenditure and 10.3 t CO2e respectively in Porvoo, with a 15.900 € annual consumption expenditure.

According to our model, the dominant carbon-producing activities in metropolitan living are heat and electricity, building and property, maintenance and operations, and private driving, accounting for approximately two thirds of the per capita carbon emissions in both case cities. However, some significant differences were found between the cities. Carbon emissions from energy consumption are 4.5 t CO2e for an average consumer in Helsinki, whereas an average consumer in Porvoo only causes a carbon footprint of 2.0 t by energy consumption due to the cleaner energy production in Porvoo. On the other hand, private driving causes 2.0 t CO2e in Porvoo, but only 1.3 t in Helsinki. The overall trip generation in Helsinki is only half of that in Porvoo, and also, the usage of public transport is on a substantially higher level in Helsinki.

One notable finding that contradicts with some earlier studies (Dodman 2009; Norman et al. 2006) is that the theoretical carbon-reducing influence of city density is easily overridden with other factors, such as the type of energy production, the energy efficiency of the housing stock, and increased use of services. In our study, Helsinki represents a metropolitan area with a denser structure and a more efficient public transport system, but still consuming around 25% more carbon emissions than the other city Porvoo in the metropolitan area.

Another surprising finding is that, even with the normalization to the same energy's emission profile, the carbon emissions from energy use are higher in Helsinki with higher density and apartment buildings as the dominant house type. While no single explanation rose from the study, a couple of factors were found to explain the findings. First, the difference in energy efficiency (energy consumption of a building per square meter) deviates in practice only moderately between an apartment building and a detached house. Second, the age of the property affects significantly the energy performance of the house (City of Helsinki 2008). As a major share of the properties in Helsinki is built between 1950 and 1970, and as the energy consumption of those buildings is 40% higher than of buildings built before 1950 or after 2000, this partly explains the findings. Finally, almost 10% of the total energy used in detached houses in Finland is based on privately acquired firewood (Kurnitski 2010, submitted (data from Heljo 2010)). This lowers substantially the amount of energy purchased and the emissions produced in Porvoo since detached houses dominate the housing stock.

Examining further the emissions from the energy use perspective, the distribution of emissions between electricity and heat should be noted. While electricity production has been a hot topic in public debate on climate change prevention, this study would indicate that heat production based on fuel and other sources actually has a higher impact on carbon consumption. In Finland, it seems that all the larger metropolitan areas rely on rather carbon-intensive heat production, but small cities like Porvoo can produce less carbon-intensive heat. It should be analyzed further if this is due to city structures, the population of the area or some other factor, and whether the situation is the same in other countries.

The reliability of this study can be assessed from at least four perspectives. First, the suitability of the method for the analysis conducted in this paper should be assessed. Second, the results need to be positioned among other studies in the same field. Third, the reliability of the input data should be analyzed and the weaknesses found should be taken into account in interpreting the results. Fourth, the reliability of the hybrid model itself should be assessed.

First, the principle method used here has been operational in regional context for decades (Miller and Blair 1985; Sargento 2009; Hewings 1969). Also, environmentally extended versions have been introduced to regional models (Cicas et al. 2007; Miller and Blair 1985; Turner et al. 2007) aiming for full inventories of emissions. The concept is thus not new, but with the presented hybrid LCA model, we have tried to avoid some of the identified problems of the direct input–output approaches.

Second, while no earlier studies exist for direct positioning, two assessments were found with per capita carbon footprint estimates in Finland, and they seem to give similar results. A calculation with the output tables of the recent Finnish IO-LCA study, ENVIMAT (Seppälä et al. 2009), resulted in 10.1 t CO2e carbon emissions per capita for an

average Finnish consumer. Junnila (2006a, b) has calculated a per capita carbon footprint of 14.6 t CO2e for Finland based on Finnish emission inventories. In addition, in World Resources Institute's ranking, the per capita carbon footprint in Finland Ltd (2005) is 13.2 t CO2e (Wikipedia 2010). Notable here is that Junnila's study and the WRI data are calculated from a producer perspective, both the approaches thus having the same limitation when compared with our current study. As was mentioned earlier, imports account for 55% of the aggregate demand in Finland, meaning that the majority of life cycle carbon emissions originate abroad. For example, Weber and Matthews (2008) found a 15% increase in the American household carbon footprint when imports were explicitly taken into account, compared directly to the EIO-LCA results. Furthermore, one additional problem of regional applications of input–output LCA is the regional industry asymmetries (Hewings 1969; Cicas et al. 2007). While we have not enhanced the output vectors of the model, the regional hybrid data, e.g., on power generation and housing prices, reduce significantly the possible bias in the hybrid model assessment.

Some of the possible uncertainties in the input data are listed below. The primary input data we used are Finnish consumer survey 2006 data (Statistics 2007). The level of detail of the data is of high quality. With over 1,000 categories of consumption goods, the data offer an excellent basis for IO-LCAs. The sample is quite large with roughly 10,000 subjects (0.2% of the population), which raises the reliability of the data. On a city scale, especially concerning the smaller cities like Porvoo, the number of subjects is substantially smaller, raising the probability of biases due to abnormal observations. To overcome this problem and test the robustness of the results, we conducted a longitudinal study with corresponding 2001 consumer survey data (Statistics 2007). While the level of consumption expenditure had risen substantially from 2001, the composition of consumption, and thus the distribution of the carbon footprint, was equal in the 2001 and 2006 data.

Public services and heavily subsidized services create another source of bias. In IO-based studies, emissions related to these are mostly excluded from the carbon footprint. In Finland, these form a noteworthy share of the total private consumption. However, we decided not to make any corrections since the assessment in the Finnish ENVIMAT study showed that the bias concerns predominantly our comprised consumption class of "health, nursing and training services," which has only minor significance in our study.

The fourth source of possible biases is the model itself. Concerning our application, these are twofold: the IO-LCA base model and the hybridization process. We chose the EIO-LCA 2002 US Industry benchmark model (Carnegie Mellon University Green Design 2008) as the basis of our hybrid model. This was done for three reasons. First, of the available IO-LCA models, the EIO-LCA 2002 model offers by far the best accuracy for the input data matching with its 428 economy sectors. This was considered important in our study due to the high level of disaggregation of the input data. Second, the output tables of the model are publicly available, enabling the construction of the type of a tiered hybrid model that we propose here. And third, only a global model would offer supreme compatibility, as imports account for more than 50% of the total consumption expenditures in Finland (Statistics 2009a, b). As the US economy is the largest in the world, it offers perhaps the closest match. Finally, it should be noticed that in the hybrid model, more than two thirds of the carbon emissions come from sectors where actual local process-based data were used.

Even after the process data enhancement, the questions of temporal (inflation and currency rate differences) and regional (industry structure differences) compatibility of the data and the model need to be assessed. First, to avoid the temporal compatibility problem, we used the PPP adjustment based on the data published by ICP (2009) following the method selected by Weber and Matthews in their recent study of the global aspects of the American household carbon footprint (Weber and Matthews 2008). The second problem related to the potential incompatibility of the industry structures, or more specifically to the incompatibility of carbon emission profiles, was assessed to have only moderate significance. First, Junnila has compared the emission profiles using both process and IO approaches, concluding that the profiles are similar in general, especially among the most important emission sources in our study (Junnila et al. 2006; Junnila 2006a, b). Second, we ran a latitudinal test using emission multipliers from the Finnish ENVIMAT study, which showed similar results in terms of the dominating sectors.

The last possible base model and data compatibility problem arises from different price perspectives. The EIO-LCA model is a producer price model, whereas the input data are based on purchaser prices. Now, in the Finnish taxation system, the difference is mainly the value added tax, meaning a scale difference type of bias. This has little significance for our study since the focus is on one single economy and the conclusions are made based on relative rather than absolute figures. There are deviating sectors where the impact of product taxes is high, such as energy and fuel sectors, but the hybrid model internalizes the majority of these impacts.

The basic idea of hybrid LCAs is to avoid the truncation problem related to process LCAs while raising the level of accuracy of IO-LCA. The hybridization process creates new problems, however. First, when conducting a hybrid LCA study, one needs to be careful in order to avoid double

counting the emissions (Suh et al. 2004). Second, the quality of the process data used in the hybridization needs to be assessed properly. We believe to have avoided the first of these problems with the careful planning of the hybrid model. Among the process data, energy production emissions seem to have rather high annual variations due to differing weather conditions. A quick sensitivity analysis on the production phase emissions of Helsingin Energia (Helsinki Energy 2009) shows that the base year selection can affect the results by roughly 10%, but the findings and conclusions remain the same.

6 Conclusions

The study presents the carbon consumption of two average consumers in the selected case cities of Helsinki and Porvoo, representing two types of metropolitan areas in Finland. The study resulted in a carbon footprint of 13.2 t CO2e for a person in Helsinki with a 17,400 € annual consumption expenditure and 10.3 t CO2e respectively in Porvoo with a 15,900 € annual consumption expenditure. The dominant carbon-producing activities in metropolitan living are heat and electricity, building and property, maintenance and operations and private driving, accounting for approximately two thirds of the per capita carbon emissions in both case cities.

However, within the cities, some significant differences were found. Carbon emissions from energy consumption are 4.5 t CO2e for an average consumer in Helsinki, whereas an average consumer in Porvoo only causes a carbon footprint of 2.0 t by energy consumption due to the cleaner energy production in Porvoo. On the other hand, private driving causes 2.0 t CO2e in Porvoo, but only 1.0 t in Helsinki. The overall trip generation in Helsinki is only half of that in Porvoo, and also, the usage of public transport is on a substantially higher level in Helsinki.

One notable finding that contradicts with some earlier studies is that the theoretical carbon-reducing influence of city density is easily overridden with other factors, such as the type of energy production, the energy efficiency of the housing stock, and increased use of services. In our study, Helsinki represents a metropolitan area with a denser structure and a more efficient public transport system, but still consuming around 25% more carbon emissions than the other city Porvoo in the metropolitan area.

7 Future research

Future research should include more metropolitan cities in different geographical regions so that the more general implications of the results could be tested. Also, the knowledge on the carbon footprint of services, especially in the service-intensive economies and cities that tend to outsource their manufacturing, should be further extended.

Acknowledgments We thank SITRA (the Finnish Innovation Fund), the Confederation of Finnish Construction Industries RT, and the YIT Corporation for supporting this research.

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